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LARGE HORIZONTAL AXIS WIND TURBINE DEVELOPMENT

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Lewis Research Center

Work performed for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology

Prepared for
Wind Energy Innovative Systems Conference
sponsored by the Solar Energy Research Institute (SERI)
Colorado Springs, Colorado, May 23-25, 1979

NOTICE

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ABSTRACT

One facet of the Federal Wind Energy Program, Large Horizontal Axis Wind Turbine Development, is being managed by the NASA Lewis Research Center. These activities consist of several ongoing wind system developments oriented primarily toward utility application. In addition, a comprehensive technology program supporting the wind turbine projects is being conducted. This paper presents an overview of the NASA activities.

First-generation-technology large wind turbines (Mod-0A and Mod-1) have been designed and are in operation at selected utility sites. Second-generation machines (Mod-2) are scheduled to begin operations on utility sites in 1980. These second-generation machines are estimated to generate electricity at less than 4¢ per kilowatt hour when manufactured at modest production rates. However, to make a significant energy impact, costs of 2 to 3¢ per kilowatt hour must be achieved. The federal program will continue to fund the development by industry of wind turbines which can meet the cost goals of 2 to 3¢ per kilowatt hour.

Lower costs will be achieved through the incorporation of new technology and innovative system design to reduce weight and increase energy capture. The national challenge, however, is associated with acceptance by the utilities of wind turbines as part of their energy generating capability and the creation of a competitive industry to produce wind turbines efficiently. The principals - government, industry, and the utilities - are currently involved in meeting this challenge.

INTRODUCTION

Since 1973, the Federal Government has sponsored an expanding research and development program in wind energy in order to make wind turbine generators a viable technological alternative to existing electrical generating capacity. The current Federal Wind Energy Program, under the sponsorship of the Department of Energy, is directed toward the development and production of safe, reliable, cost-effective machines which will generate significant amounts of electricity.

One element of the Federal Wind Energy Program is Large Horizontal Axis Wind Turbine Development, which is being managed by the NASA Lewis Research Center. This activity consists of several ongoing wind system developments oriented primarily toward utility application. In addition, a comprehensive technology program supporting the wind turbine projects is being conducted. This paper presents an overview of the NASA activities. More detailed descriptions of the projects are presented in references 1 to 3.

WIND TURBINE DESCRIPTION

A typical wind turbine that NASA is developing is shown in figure 1. The rotor and drive train are mounted on a tower 100 to 200 feet high. The axis of rotation is parallel to the ground - thus the name horizontal axis wind turbine. The rotor consists of two blades. Rotor diameters of the machines currently under development range from 125 to 300 feet. The rotor operates at a low rotational speed of 20 to 40 rpm, and its output terminates in a gearbox which is simply a speed increaser (fig. 2). The gearbox increases the rotational speed to 1800 rpm, as shown, and the high-speed shaft drives a standard synchronous alternator. The alternator output is connected to a utility network. There are two controls on the wind turbine: (1) a yaw control, consisting of an electric motor, a pinion shaft, and a bull gear, which orients the machine in the direction of the wind, and (2) a pitch control, which moves the blades and controls the power. The pitch control is very similar to that of an aircraft propeller.

ONGOING ACTIVITIES

The wind turbines, either operational as experimental machines or under development, are illustrated schematically in figure 3. Three machines are shown. The Mod-0 and Mod-0A machines have rotor diameters of 125 feet and power outputs of 100 to 200 kilowatts. The Mod-1 is a larger machine, 200 feet in diameter, which is rated at 2000 kilowatts. An even larger machine, the Mod-2, is 300 feet in diameter and generates 2500 kilowatts; it looks different from the Mod-0A and Mod-1. The Mod-2 was developed later than the Mod-0A and Mod-1, and it was designed with a new technology base.

The annual energy output of these machines is shown in figure 4. At a site with an annual mean wind speed of 15 mph, the annual energy output of the Mod-0A machine is approximately 1000 megawatt hours per year. The Mod-1 machine will produce approximately five times the annual energy of the Mod-0A machine, and the Mod-2 produces 10 000 megawatt hours, or enough electricity for 1000 average homes.

The Mod-0A, Mod-1, and Mod-2 machines are being used (or are planned to be used) as experimental machines at utility sites. The activation dates for these machines are shown in figure 5. Four Mod-0A wind turbines are planned. Two machines are already operationing at Clayton, New Mexico, and Culebra Island, Puerto Rico. A third machine will be placed at Block Island, Rhode Island, in 1979, and a fourth machine

will be erected in Hawaii in 1980. The results of 1 year of successful operation at Clayton, New Mexico, have been published in reference 1.

The Mod-1 wind turbine is planned for initial operation at Boone, North Carolina, in mid-1979, and the Mod-2 development is currently planned as a three-machine program. The three machines may be placed at a single site in 1980 for a 7.5-megawatt demonstration.

All the wind turbines in operation or under development are automatically (microprocessor) controlled. Their operating map is shown in figure 6. The units start when the wind velocity reaches a range from 7 to 11 mph (at a 30-ft height). As the wind speed increases, the power output also increases until rated power is attained. The power is then held constant at the rated value until a wind velocity of approximately 35 mph (at 30 ft) is reached. At wind velocities exceeding 35 mph, the wind turbine is shut down. It simply does not pay to design the machines for very high wind speeds. The annual energy content of the wind is small at high velocities because the wind does not reach these velocities very often on an annual basis. In addition, if the machines were designed to operate in high winds, the machine cost and weight would be excessive.

Mod-0 (100 kW) Wind Turbine

Mod-0 was the first large wind turbine that was designed and built by NASA (fig. 1). It is located at the NASA Plum Brook Station at Sandusky, Ohio. Mod-0 has been in operation since 1975 as a research machine and is utilized to validate wind turbine design techniques (computer codes) and to demonstrate new concepts that have potential to increase reliability and lower machine capital cost. Mod-0 tests and operations are closely focused to the support of ongoing projects conducted by industry. In this way, Mod-0 has made major contributions to the electrical and structural design of the machines currently under development (Mod-0A, Mod-1, and Mod-2).

Mod-0A (200 kW) Wind Turbine

The objective of the Mod-0A program was to gain early experience with wind turbines at utility sites. As stated previously, two machines are currently operational (fig. 7). The Mod-0A machine was designed and built by NASA. Westinghouse Electric Corporation is supporting the program and was the installation and support contractor for the Clayton machine. Westinghouse is assuming increasing responsibility for the other Mod-0A machines. NASA and DOE have been pleased with the success of the Clayton machine over the past year. The electrical, structural, and performance aspects of the basic system design have been validated. There have been no problems with the interface between the wind turbine and the utility. The machine is routinely synchronized to the utility grid and has provided approximately 3 percent of the Clayton power over the past year. The utility personnel are capable of operating the machine without difficulty. As expected, we had early operational difficulties with some of the hardware, but overall the operation has been

very successful. The weekly and monthly machine availability in 1979 is shown in figure 8. As can be seen, having overcome early operational difficulties, we expect to reach the goal of 90 percent in 1979.

Mod-1 (2000 kW) Wind Turbine

The objective of the Mod-1 program (similar to Mod-0A) is to gain early operational experience with a megawatt output wind turbine at a utility site. The Mod-1 machine except for the blade was designed and built by the General Electric Company; the blade was built by the Boeing Engineering and Construction Company. The Mod-1 is a scaled up version of the Mod-0A machine. The machine and blade are shown in figures 9 and 10. The machine fabrication and installation are complete, and the acceptance tests and final machine checkout are in process at Boone, North Carolina. The operational phase of the program is expected to begin in mid-1979.

Mod-2 (2500 kW) Wind Turbine

The objective of the Mod-2 development was to design a cost-competitive, safe, reliable megawatt wind turbine for utility application at moderate wind sites (14-mph annual average at 30 ft). A model of the machine is shown in figure 11. This was the first machine designed to cost. The goal is for the 100th machine to generate electricity at less than 4¢ per kilowatt hour. The Boeing Engineering and Construction Company is the prime contractor for Mod-2. To date, there is every reason to expect that the cost goal will be met. The Mod-2 design has benefited extensively from prior experience. Test results from the Mod-0 and Mod-0A programs have been used to validate computer codes and identify and validate new design concepts that have been applied to Mod-2. In addition, the design experience from the Mod-1 project has been used. The key to the Mod-2 success to date has been the flexible structural system design, which has led to a relatively lightweight low cost machine with high annual energy output. Long lead hardware has already been ordered for the machine, and operations are scheduled for 1980.

COST OF ELECTRICITY

The cost of electricity (COE) in cents per kilowatt hour is plotted as a function of mean wind speed in figure 12 for the NASA wind turbines either operational or under development. This COE plot reflects the machine capital costs for the second units that are built and assumes that the machines will operate and generate electricity 90 percent of the time that the wind is in the proper speed range. The cost of electricity is calculated by a formula for new technologies recommended by the Electric Power Research Institute:

$$\text{COE} = (\text{machine capital cost})(\text{fixed charge rate}) + (\text{operation and maintenance cost})/\text{annual energy}$$

The fixed charge rate used was 0.18.

Several conclusions can be drawn from figure 12. The COE is dramatically affected by the site mean wind speed, and the identification of attractive wind sites is important to the application of this technology. The Mod-0A (200-kW) machine is associated with relatively high cost of electricity, 30 to 50¢ per kilowatt hour. A significant improvement (approx. 2 to 1) has been made in the Mod-1 (2000-kW) COE. Keep in mind that these two wind turbines are the same basic design; however, Mod-1 is a much larger machine. There are definite economies of scale which result in a major reduction in the Mod-1 COE from the Mod-0A COE. With Mod-2, in turn, another large cost reduction (2 to 1 compared with Mod-1) is expected as a result of improved technology incorporated into the Mod-2 design. The Mod-2 machines that will be operational in 1980 are expected to produce electricity at 14-mph wind sites at costs below 8¢ per kilowatt hour.

The dotted curve shows the projected Mod-2 costs for production units. We anticipate that these units will be cost-competitive in certain areas with attractive wind sites where current fossil fuel costs are high. However, before there is broad market penetration, further reductions in COE must be achieved. We believe that these reductions can be made. New system developments currently planned will incorporate new technology which will result in lighter weight, lower cost systems.

The contribution of the wind turbine subsystem elements to the cost of electricity is shown in figure 13. When the Mod-0A and Mod-2 rotor costs are compared, it is apparent that Mod-2 design improvements have resulted in major rotor cost reductions (2 to 1). In addition, the rotating machinery on top of the tower (blades, gearbox, generator, etc.) now comprises approximately one-half of the wind turbine costs, which signifies an economically balanced design.

The cost contributions of the other elements are fairly evenly distributed. However, it is believed that further reductions in costs of all of the subsystems can be achieved, with the largest reductions still to be gained in the rotor and drive trains.

DEVELOPMENT ASSESSMENT

Technology

Major improvements have been made in wind turbine technology over the past 5 years. As a result, wind turbine system design is understood. The design tools are in an advanced state of development and are available to U.S. industry. Operational machines at utility sites have validated the basic system, electrical, structural, and mechanical designs. The compatibility of the single unit wind turbine with utility interfaces has been successfully demonstrated. Further operational experience is required to address long-term reliability. Additional blade development is required and is under way to reduce cost and weight. Metal, fiberglass, and wood blades are all currently attractive candi-

dates. A 150-foot fiberglass blade built by Kaman is shown in figure 14. Planetary gearboxes in large sizes may also require some development.

Environment Issues

No serious environmental issues have been identified which would impede the development of large wind turbines. Experience to date has shown that wind turbines are safe, quiet, and clean; however, television interference is a siting consideration.

Economics and Market Potential

Large megawatt machines have the greatest potential for application in utility networks because of economies of scale and are the only machines that will generate significant amounts of electricity. In most applications, wind turbines must produce electricity at 2 to 3 per kilowatt hour to have wide application as a utility fuel saver at current fuel prices. The Mod-2 machine approaches these costs, and moderate COE reductions and/or higher fuel costs will result in substantial market potential.

CONCLUDING REMARKS

First-generation-technology large wind turbines (Mod-0A and Mod-1) have been designed and are in operation at selected utility sites. Second-generation machines (Mod-2) are scheduled to begin operations on a utility site in 1980. These second-generation machines are estimated to generate electricity at less than 4¢ per kilowatt hour when manufactured at modest production rates. However, to make a significant energy impact, costs of 2 to 3¢ per kilowatt hour must be achieved. The Federal program will continue to fund the development by industry of wind turbines which can meet the cost goals of 2 to 3¢ per kilowatt hour. These lower costs will be achieved through the incorporation of new technology and innovative system design to reduce weight and increase energy capture. The national challenge, however, is associated with acceptance by the utilities of wind turbines as part of their energy generating capability and the creation of a competitive industry to produce wind turbines efficiently. The principals - government, industry, and the utilities - are currently involved in meeting this challenge.

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1. Glasgow, J.; and Robbins, W.: Utility Operational Experience on the NASA/DOE 200 kW Wind Turbine. Paper presented at Energy Technology VI Conference, Washington, D.C., Feb. 26-28, 1979.

2. Mod-1 Wind Turbine Generator Analysis and Design Report - Executive Summary. General Electric Co., Philadelphia, Pa., under NASA Contract NAS3-20058, Report No. DOE/NASA/0058-79/3, NASA CR-159497, Mar. 1979.

3. Lowe, J.: Status and Outlook of Megawatt Size Wind Turbines for Utility Applications. Paper Presented at Energy Technology VI Conference, Washington, D.C., Feb. 26-28, 1979.

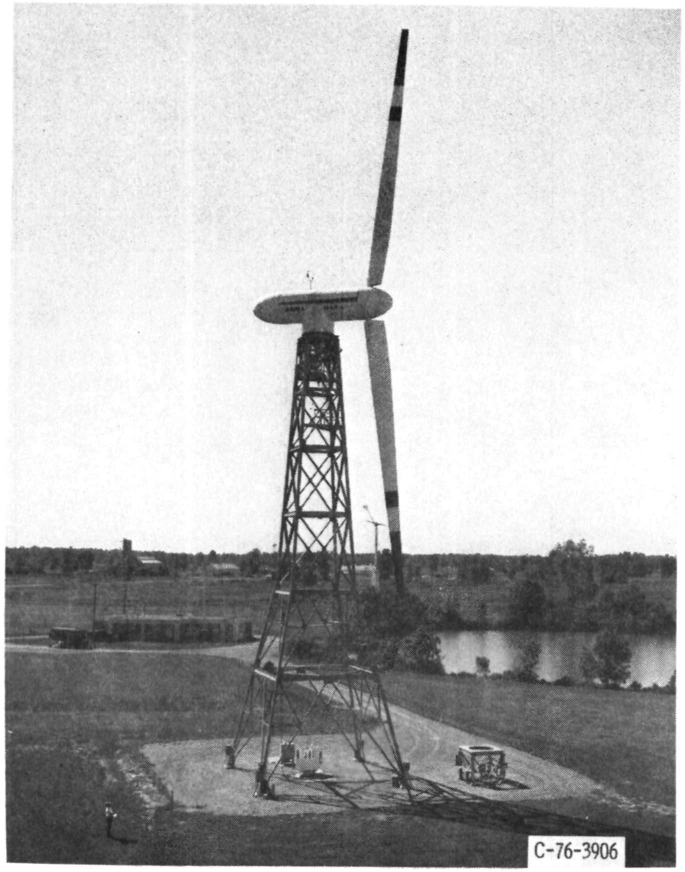

Figure 1. - Horizontal axis wind turbine (Mod-0).

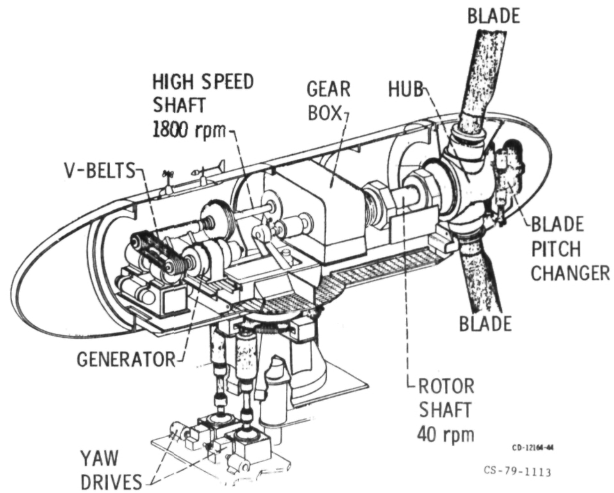

Figure 2. - 200 kW wind turbine nacelle interior.

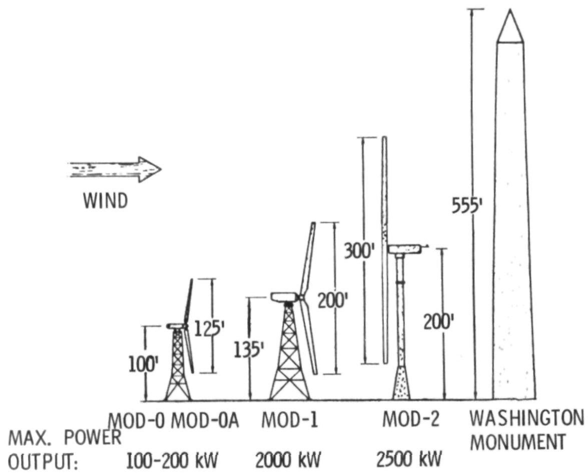

Figure 3. - Large wind turbines.

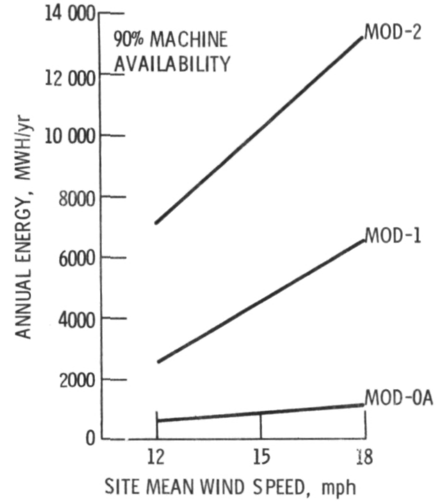

Figure 4. - Annual energy output.

	1977	1978				1979				1980				1981	
	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
MOD-0A															
CLAYTON, NEW MEXICO	▼														
CULEBRA, PUERTO RICO			▼												
BLOCK ISLAND, RHODE ISLAND							▽								
KAENA POINT, HAWAII											▽				
MOD-1															
BOONE, NORTH CAROLINA							▽								
MOD-2											▽	▽	▽		

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Figure 5. - Actuator dates for large wind turbines.

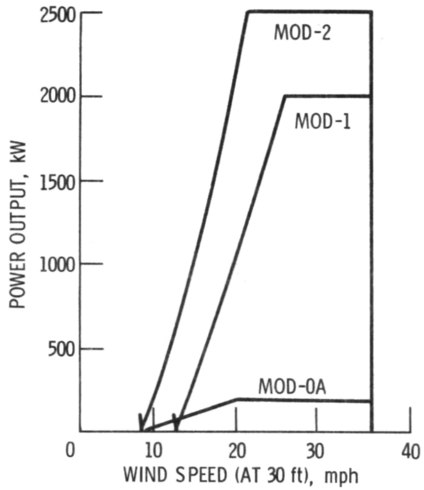
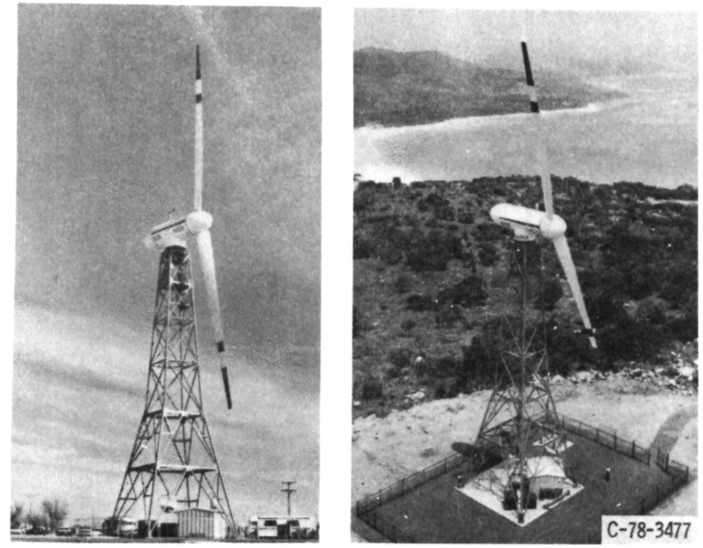
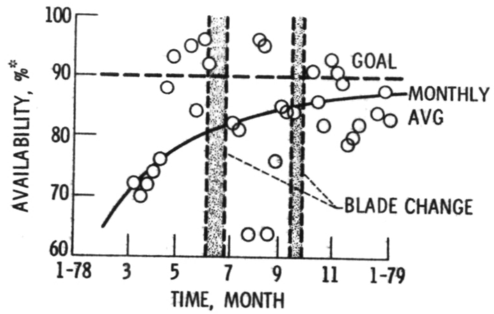


Figure 6. - Wind turbine operating range.



CLAYTON, NEW MEXICO CULEBRA, PUERTO RICO

Figure 7. - Clayton and Culebra machines.



$$^{*}\text{AVAILABILITY} = \frac{\text{hr OF SYNCHRONOUS OPERATION}}{\text{hr BETWEEN CUT-IN \& CUT-OUT WIND SPEED}} \times 100.$$

Figure 8. - Mod-0A availability.

Figure 9. - Mod-1 Machine.

Figure 10. - Mod-1 blade.

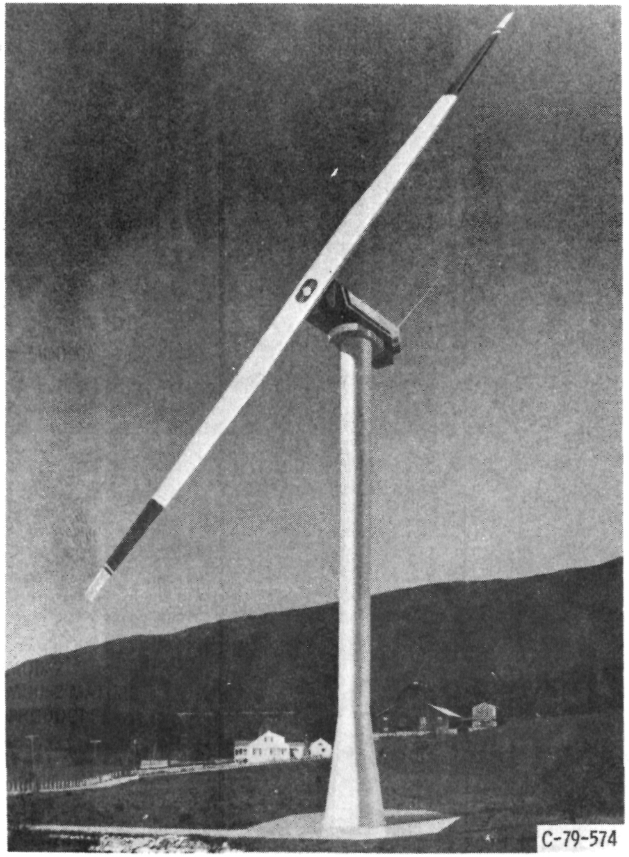


Figure 11. - Mod-2 wind turbine.

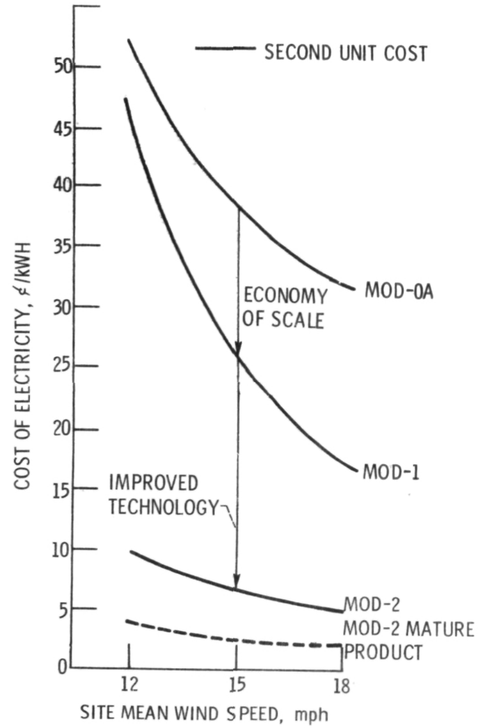


Figure 12. - Cost of electricity.

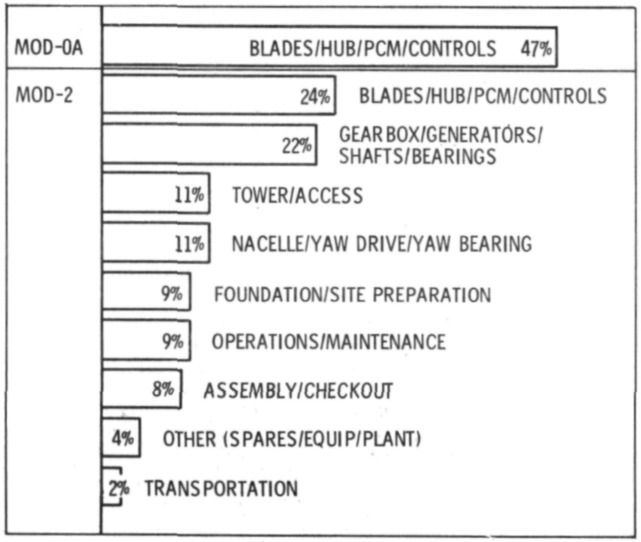


Figure 13. - Contribution of design elements to COE.

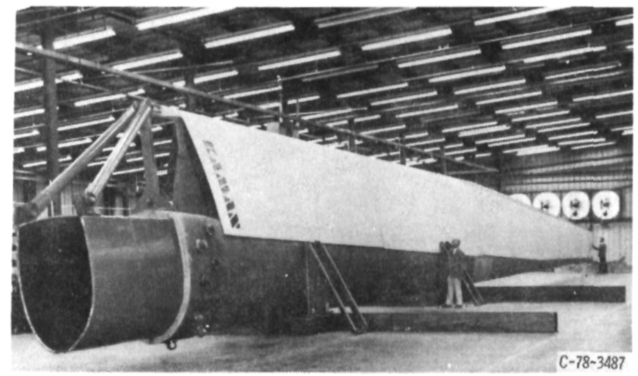


Figure 14. - Kaman 150-ft fiberglass blade.

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